N71-12250

NASA TECHNICAL MEMORANDUM

NASA TM X-52930

NASA TM X-52930

A DESIGN OPTIMIZATION OF AN OUT-OF-CORE THERMIONIC CONVERTER

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TECHNICAL PAPER proposed for presentation at
1970 Thermionic Conversion Specialists Conference sponsored
by the Institute of Electrical and Electronics Engineers
Miami, Florida, October 26-29, 1970

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Abstract

The design optimization of an out-of-core thermionic converter module is described. The module is a cylindrical converter, heated and cooled by heat pipes, with an integral finned radiator. Performance data illustrating the dependence of electrode efficiency and power density on emitter and collector temperature are used as input data. Design parameters such as electrode thickness and area, and current-voltage operating points are varied and the minimum specific weight design is determined. For fixed converter designs the sensitivity of performance to changes in heat pipe vapor temperature, electrical load, and radiator area is also explored.

Introduction

The staff at Lewis Research Center has recently completed a preliminary evaluation of the out-of-core thermionic concept. The study[1] emphasized recent technological developments and thermionic performance improvement. For the concept studied, the thermionic converters were mounted in the radiator and joined to the heat source by long heat pipes. Due to the short time period available for initial study, the component weight estimates were only preliminary. Subsequently detailed component weight analyses[2-3] were conducted.

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The thermionic converter module design is typical of that described by Kroeger.[4] To analyze the module an engineering model was developed which predicts electrical and thermal performance based upon actual measured performance values. With this model one can predict module performance over a range of electrode temperatures and electrical load conditions. Furthermore one can study the influence of variations in module design on the module specific weight.

The analysis employed the performance data for polycrystalline rhenium, niobium converter reported by Kascak and Williams.[5] These data reflect the performance levels achievable in 1967 but much higher performance levels have been recently reported for converters with single crystal rhenium and etched tungsten emitter, references 6 and 7 respectively. However, the Kascak and Williams data includes detailed caliormetric measurements over a wide range of collector temperatures, which was unavailable for the high performance materials. This relatively low performance data was used to develop the calculational procedure and study the influence of collector temperature on module design. Module specific weight calculations were made at selected points using the higher performance data.

Engineering Model

An engineering model has been developed to analyze the thermal and electrical performance of a single out-of-core thermionic converter and determine the minimum specific weight design. A cylindrical converter is assumed which is heated by a high temperature heat pipe and cooled by a vapor chamber radiator.

Using the model, the designer selects an initial design, independently varies parameters such as; electrode area, electrode thickness, radiator area, current density, etc., and calculates a set of module specific weights from which the minimum value is selected.

A novel feature of the electrical and thermal analysis is the use of both measured calorimetric and electrical performance data to obtain empirical expressions for the electrode voltage and the thermal flux at the collector for selected values of current density, emitter and collector temperature. To develop these expressions, one selects a set of static performance data for which the cesium reservoir pressure is optimized for highest voltage at a fixed current density. This set must include the electrode voltage and the collector thermal flux measured over a broad range of current densities, emitter and collector temperatures. A multiple regression analysis of the data results in a functional expression of the form of equation 1, which described the electrode voltage $V(T_E, T_C, J)$. A second identical functional form describes the thermal flux at the collector, $Q(T_E, T_C, J)$.

$$\begin{aligned} V(T_E,T_C,J) = {} & B0 + B1 \times J + B2 \times T_C \\ & + B3 \times T_E + B4 \times J \times T_C \\ & + B5 \times J \times T_E + B6 \times T_E \times T_C \\ & + B7 \times T_C \times T_C + B8 \times T_E \times T_E \\ & + B9 \times J \times T_C \times T_C + B10 \times J \\ & \times T_E \times T_E + B11 \times T_E \times T_C \end{aligned} \tag{1}$$

$V(T_E,T_C,J)$ is the electrode voltage......volts
where J is the diode current density..Amp/cm^2
T_E is the emitter temperature....^oK
T_C is the collector temperature..^oK
B0, B1,....B11 are a set of coefficients.

The B-set of coefficients is calculated to obtain the highest correlation between predicted and measured performance data with the least standard error of estimate.

Figure 1 shows a schematic of the thermal transport model used. The major portion of the transport is $Q(T_E, T_C, J)$ and the electrical power P_e, $(J \times V)$ both of which are obtained from the correlation described above. The voltage, V, is corrected for voltage drops in the electrode. Other thermal transport terms which must be calculated are Q_{lead}, the loss in the electrical lead and Q_{end}, the heat loss from the inactive ends of the converter. The lead conduction term is calculated assuming no radiation and that the cool end is at the radiator temperature and the hot end at the emitter temperature. One half of the Joule heat generated in the lead is assumed to be returned to the emitter. Q_{end} consists of an

Presented at the 1970 Thermionic Conversion Specialists Conference, October 26 through 29, 1970, Miami, Florida

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electron cooling term, and a radiation term. The electron cooling loss is calculated using an assumed work function for the end area. The radiation loss is calculated using an assumed effective emittance and the surface temperatures. The thermal conduction losses in the end section are negligible. The designer can determine the degree of influence of these terms on performance by varying the lead dimensions, and the inactive length of the converter.

Actually, two calculational techniques were used in the module analysis. In the first technique; lithium vapor temperature, T_{Li}; the collector surface temperature, T_C and J are used as inputs. A converter design is specified and the Newton-Raphson technique is used to converge on a solution for the emitter temperature T_E, electrode voltage $V(T_E, T_C, J)$, and $Q(T_E, T_C, J)$. An electrical lead design which maximizes the converter efficiency is calculated, the radiator area required for heat rejection is established and the converter weight is determined. The specific weight is calculated by dividing the total module weight by the net electrical power. J is then incremented and the radiator area and the lead design are recalculated to allow for changes in heat rejection and current flow. The module specific weight is then recalculated.

For the fixed converter design, the lowest specific weight is established for the range of J values used. Then T_C is incremented and the entire process is repeated until the minimum specific weight is determined for the initial T_{Li} value.

In the calculational method described above only the design of the converter electrodes was fixed with lead design and radiator area recalculated for each operating condition. Therefore, the changes in estimated performance are not typical of a fixed module design. In the alternate calculational method a fixed module design is assumed, that is, the converter as well as electrical lead and radiator area are fixed, and the effect of off-design operating conditions is explored.

In order to establish the minimum specific weight module design, physical parameters such as electrode area, radiator area, and lead design are incremented about the initial design and the resulting specific weights are compared.

Reference Diode Description

A schematic cross section of the reference converter is shown in figure 2. E. W. Kroeger[4] describes the construction of this diode in detail. The design of this reference converter was based upon a preliminary analysis.[2,3] The cylindrical converter has a rhenium emitter and niobium collector. The 73 sq cm emitter is 2.28 cm (.902 inch) in diameter and has an active length of 10.15 cm (4.0 inches).

The emitter electrode surface .51 mm (20 mil) of rhenium is chemically vapor deposited onto a 1.42 cm (56 mil) thick tantalum cylinder. This is, in turn, shrunk fit onto a T-111 (Ta-8W-2Hf) heat pipe. The heat pipe outer diameter is 1.9 cm (.75 in.) and the wall thickness is 1.0 mm (40 mil). Lithium is the working fluid in the heat pipe. The thickness of the lithium film on the inner diameter of the heat pipe is .75 mm (30 mil). The 3.86 mm (152 mil) thick niobium collector is separated from the emitter structure by a .23 mm (9 mil) interelectrode space. A .38 mm (15 mil) layer of sodium and wick wet the outer diameter of the collector structure. A total axial length of 2.5 cm (1.0 inch) is required to accommodate the metal-to-ceramic seal and the end closure.

The sodium vapor chamber radiator is constructed of .76 mm (30 mil) Nb-1Zr sheet. The rectangular chamber is divided into four smaller chambers by .51 mm (20 mil) Nb-1Zr partitions. The segmenting of the chamber is to provide for partial cooling if a meteoroid were to puncture one or more of the four chambers permitting the escape of the sodium vapor.

Heat Transfer Discussion

Kascak and Williams[2] tested a cylindrical thermionic converter having a vapor-deposited rhenium emitter and a niobium collector with a .25 mm (10 mil) interelectrode spacing. Both electrode efficiency and power density were measured over an emitter temperature range of 1600° K to 2050° K and over a collector temperature range of 873° K to 1173° K.

The regression analysis of this data results in two sets of coefficients; one set for the electrode voltage expression, the second set for the thermal flux expression. When the original data is compared with data generated using the resulting expressions, the correlation coefficient is 0.98. These two sets of coefficients are used in the model.

The end losses in the converter Q_{end} are calculated assuming that 2.5 cm (1.0 inch) of axial heat pipe length is required for the closure for all electrode areas. The two heat transfer mechanisms in the ends are radiation and electron cooling. The radiation term is calculated from the surface temperatures assuming an effective emittance of 0.26. In order to permit stable operation at low emitter temperatures, the reference design includes an igniter ring in each end. This ring operates under short-circuit conditions and provides an additional source of cesium ions. The electron cooling of the igniter ring is calculated from the surface temperature when a work function is assumed. For the exposed tantalum electrode surface a cesiated work function of 3.2 eV is reasonable. In this design the radiation term is typically ten times larger than the electron cooling term.

The current carrying lead is niobium. The dimensions of this lead are important design parameters which can be either fixed or adjusted to obtain the highest possible converter efficiency.

The radiator emittance is assumed to be .9 and it rejects its heat to a 300° K sink. The radiator area is calculated from the total heat rejected and the radiator temperature, T_R, which is calculated from the collector temperature and the collector heat flux. A 5° K temperature drop is assumed in the chamber in addition to temperature losses which are calculated through the sodium film and the vapor chamber walls. In this design, radiation is permitted from both sides of the vapor chamber fin. The vapor chamber width is taken equal to the emitter length plus 1.22 cm (.48 in). The height of the chamber is the collector outer diameter plus 1.27 cm (.5 inch). The chamber length is determined from the required radiator area.

Data and Results

For the reference converter at T_{Li} of 1810° K and for the rhenium-niobium data of reference 5, figures 3 and 4 show the variation of converter performance with changes in J, for four T_C values. Since T_C is fixed, the radiator area changes with J. And for each (J, T_C) combination, the lead design is recalculated to maximize the converter efficiency.

In figure 3 both electrode and converter efficiencies are shown as a function of J. The influence of the current dependent loss terms cause the converter efficiency to maximize at 6 Amp/cm^2, a current density lower than that required for maximum electrode efficiency. At this lower current density a T_C of 975° K produces the highest electrode efficiency and the highest converter efficiency.

Figure 4 illustrates the influence of J on specific weight and output power. Over the range of current densities studied the highest output power was achieved at a T_C of 1025° K. Neglecting the weight of the collector structure, the radiator weight is over 50 percent of the total module weight. For the collector temperature values studied the minimum specific weight is 16.8 lb/Kwe and it occurs at a current density of 7.5 Amp/cm^2.

Figure 5 demonstrates the influence of substrate thickness and electrode area on module specific weight. The lithium vapor temperature is set at 1810° K for this portion of the study. For a selected substrate thickness and a selected electrode area, the module specific weight is calculated for a large number of T_C and J values with current carrying leads optimized. The specific weight value plotted in figure 5 is the minimum value thus obtained for the selected substrate thickness and electrode area. For small electrode areas (short emitter lengths), the end loss term is an important fraction of the total thermal power required. While for large emitter areas (longer electrodes), electrode voltage drops increase due to both higher currents and higher electrode resistance. Therefore, a minimum specific weight results from a tradeoff between end losses and electrode voltage drops.

At fixed emitter areas a decrease in the substrate thickness increases both the emitter temperature and the electrode performance. However, this gain can be offset by the increased electrode resistance and increased electrode voltage drops. Over the thickness range examined, the voltage loss term is not as significant as the increase in performance. For the reference converter, the .41 mm (16 mil) substrate thickness is the most desirable of those examined. The total wall thickness is 2.69 mm (106mil) when heat pipe wall and emitter thickness are included. However, if 1.42 mm (56 mil) substrate thickness cannot be decreased from a structual standpoint an increase in electrode area would result in a slight reduction in specific weight.

Figure 6 illustrates the influence of radiator area on net output power for three T_{Li} values. For each temperature, the lead design is fixed for minimum specific weight and these conditions are shown by the dashed line. The solid line is the power available if one is permitted to redesign the lead as the radiator area is changed. The fixed lead design does not lead to a significant power loss.

For the reference design at 1810° K the specific weight minimizes with a radiator area of 560 cm^2 (0.6 sq ft). This area is provided by a vapor chamber measuring 11.4 cm along the diode by 24.4 cm long (4.4 in x 9.6 in), radiating from two sides. In figure 6, at minimum specific weight the required radiator area increases with T_{Li}, but the specific radiator area decreases from .42 M^2/Kwe (4.5 ft^2/Kwe) at 1710° K to 21 M^2/Kwe (2.3 ft^2/Kwe) at 1910° K.

In figure 7 the radiator area is fixed at 560 cm^2 (0.6 ft^2) and the lead cross-sectional area per unit length (A/L) is fixed at 1.0 cm^2/cm. These are the conditions for minimum specific weight of the reference converter at 1810° K. The dashed lines indicate the expected improvement if lead and radiator designs are reoptimized.

The importance of high source temperature is demonstrated by halving of the specific weight as the vapor temperature is increased from 1700° to 1900° K. For the reference converter at a T_{Li} of 1810° K the specific weight minimizes at 16.7 lb/Kwe with a converter efficiency of .060 and an output of 202 watts. This power is obtained at J of 7.54/cm^2 with a usable voltage of .371 volts. The emitter temperature is 1783° K and the collector temperature is 1050° K.

If higher performance electrode materials[3,4] are utilized in the reference converter (a 73 cm^2 electrode area and a 1.42 mm tantalum emitter substrate), one would expect performance gains for the reference converter. At T_{Li} of 1830° K the calculations using rhenium, niobium data of Pigford and Thinger and the reference converter predict a net output power of 386 watts at 9 Amp/cm^2 with a calculated converter efficiency of .113. The resulting module specific weight is 10.9 lb/Kwe. At a T_{Li} of 1810° K the tungsten, niobium data of Wilson and Lawrence yields a net output of 515 watts at 7.8 Amp/cm^2 with a calculated converter efficiency of 0.125. The resulting module specific weight is 9.7 lb/Kwe. These specific weight reductions of 40 percent represent substantial improvements and even greater reductions may be possible by detailed optimization when additional performance data is acquired over a broader range of variables.

Concluding Remarks

A detailed engineering model has been developed to study the performance of an out-of-core thermionic module which is mounted in the radiator. 1967 polycrystalline rhenium, niobium converter performance data was used in the model since it included calorimetric data taken over a broad range of collector temperature which is an important design parameter. Using a reference converter design with 73 cm^2 electrode area, a minimum specific weight of 16.7 lb/kWe was predicted at a module efficiency of .060 at a lithium vapor temperature of 1810° K.

When higher performance materials such as single crystal rhenium or etched tungsten are assumed for the electrodes of the reference converter, the specific weight is reduced to nearly 10 lb/kWe, a 40 percent savings, and the module efficiency nearly doubles to $.119 \pm .005$. An even greater savings may be possible for a fully optimized design using the higher performance data is acquired over a broad range of collector temperature.

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SCHEMATIC DIAGRAM OF HEAT TRANSFER TERMS

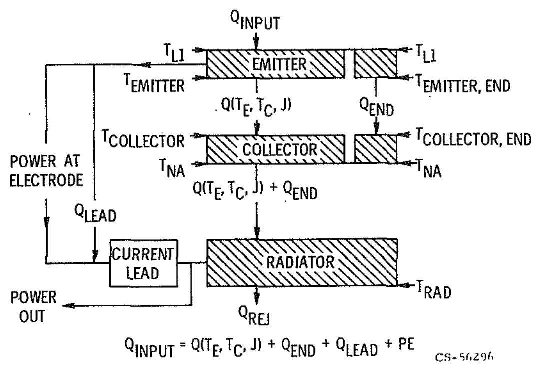

Figure 1

OUT OF PILE THERMIONIC MODULE

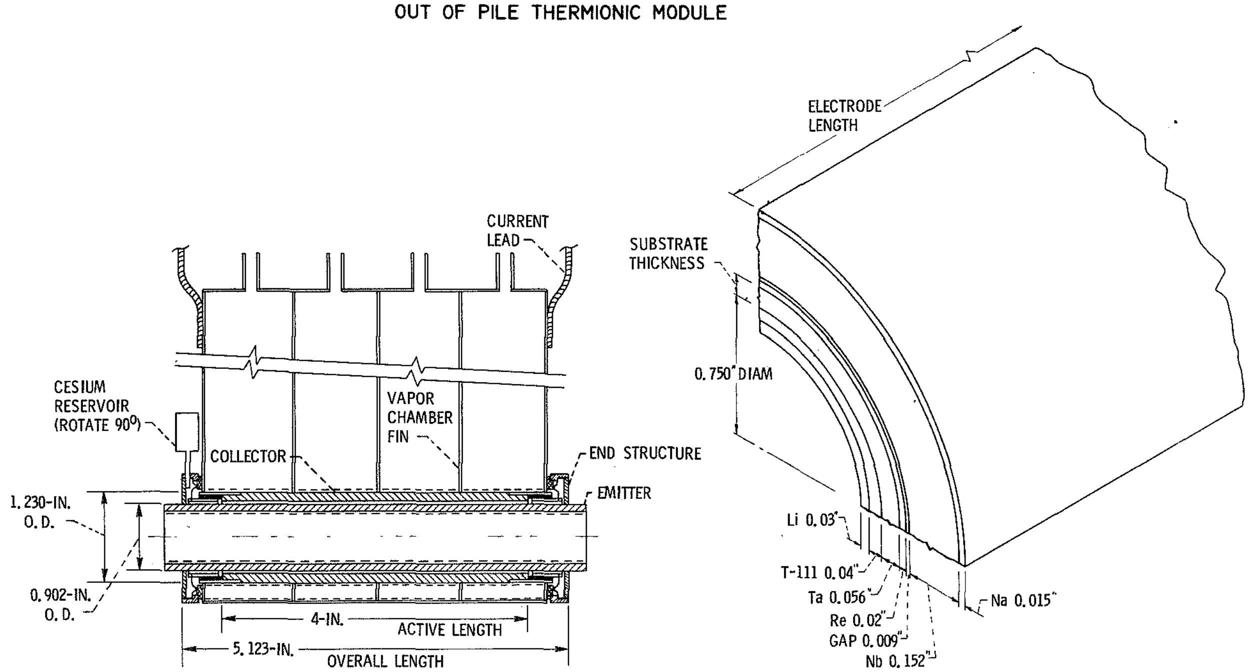

Figure 2

PERFORMANCE OF REFERENCE CONVERTER

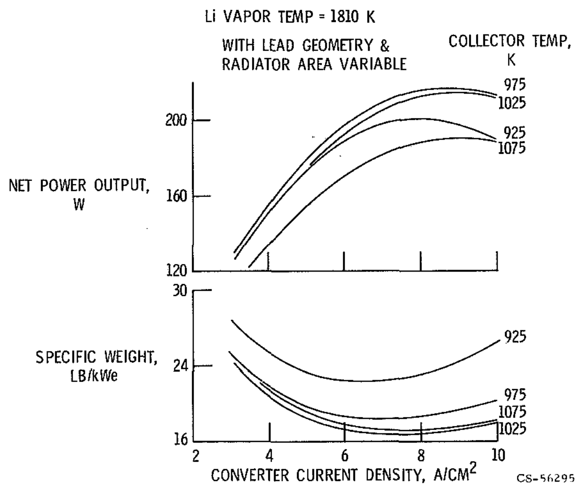

Figure 4

EFFICIENCY OF REFERENCE CONVERTER

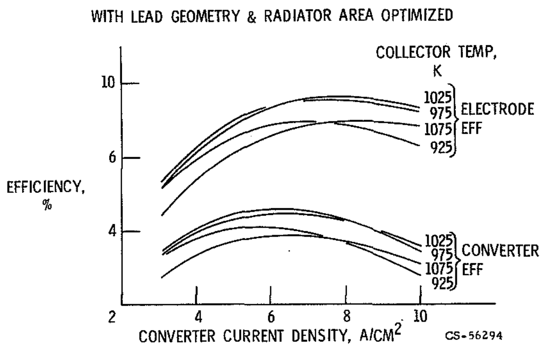

Figure 3

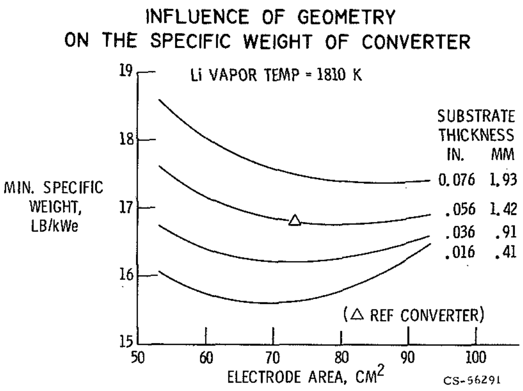

Figure 5

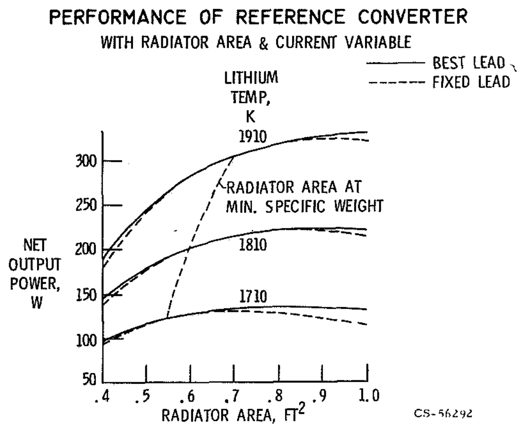

Figure 6

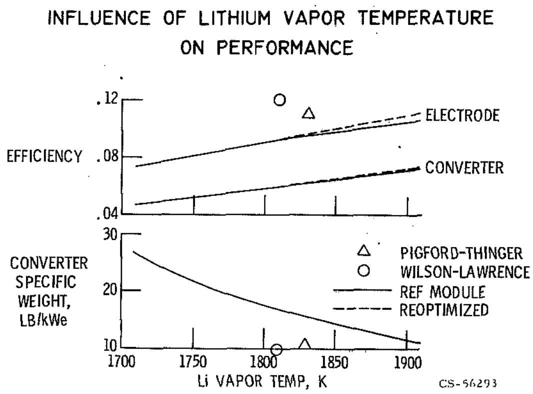

Figure 7